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(54) **Method and apparatus for demodulating signals in a well logging while drilling system**

(57) In apparatus for obtaining subsurface measurements during drilling in a fluid-filled borehole digital data representative of downhole measurements are PSK modulated by momentarily unidirectionally changing the frequency of an acoustic carrier signal. An uphole receiving subsystem converts the modulated acoustic carrier waves to electronic signals and includes a bandpass filter (110) which has its centre frequency offset from the nominal carrier frequency in the direction of the unidirectional frequency change applied during modulation, and which may be skewed in the same direction as the offset.

The output signal from the filter (110) is coupled to a phase-locked loop (120) which locks onto the carrier of the received signal, and provides timing signals for the demodulation. The phase-locked loop (120) includes a variable bandwidth filter (300), and a controller (205A) to change the bandwidth of the filter (300) as a function of the input signal.

The signal applied to the control terminal of the VCO (204) of the loop is compensated as a function of transitions in the received signal to account for the difference, arising from the unidirectional nature of the carrier modulation, between the nominal frequency of the carrier and the average frequency of the received signal.

Capacitors in the varible filter (300) are precharged to appropriate voltages to prevent loss of phase-lock during switching between different loopwidths.

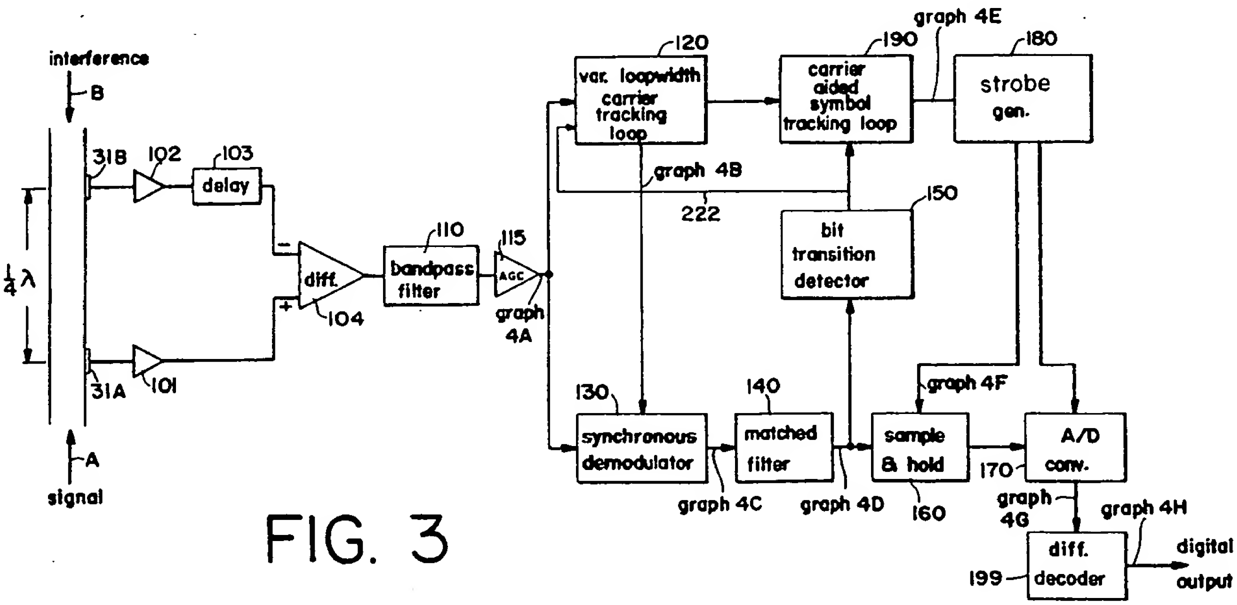

FIG. 3

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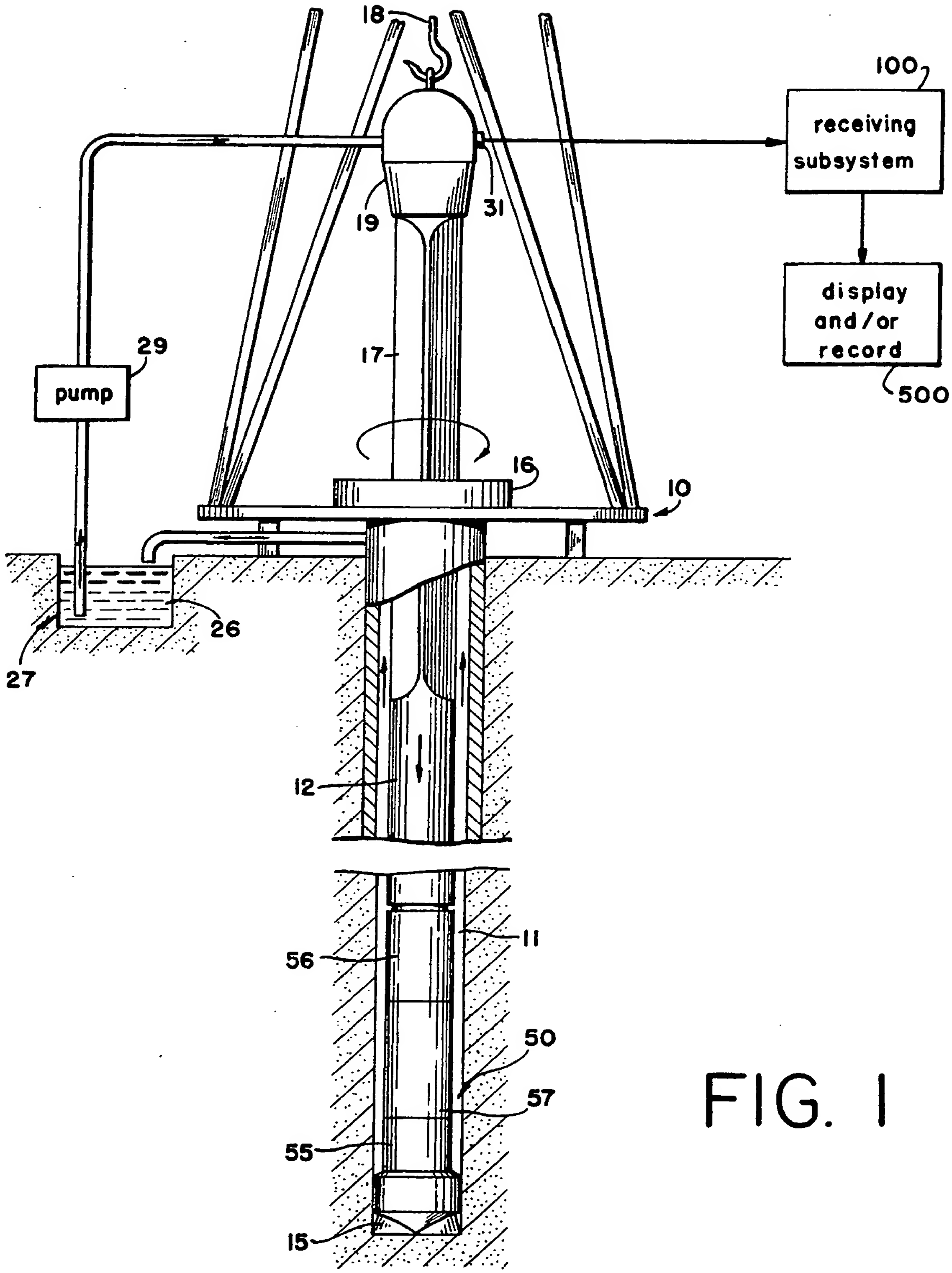

18
100
receiving subsystem
19
31
display and/or record
500
29
pump
17
16
10
26
27
12
56
11
50
57
55
15

FIG. 1

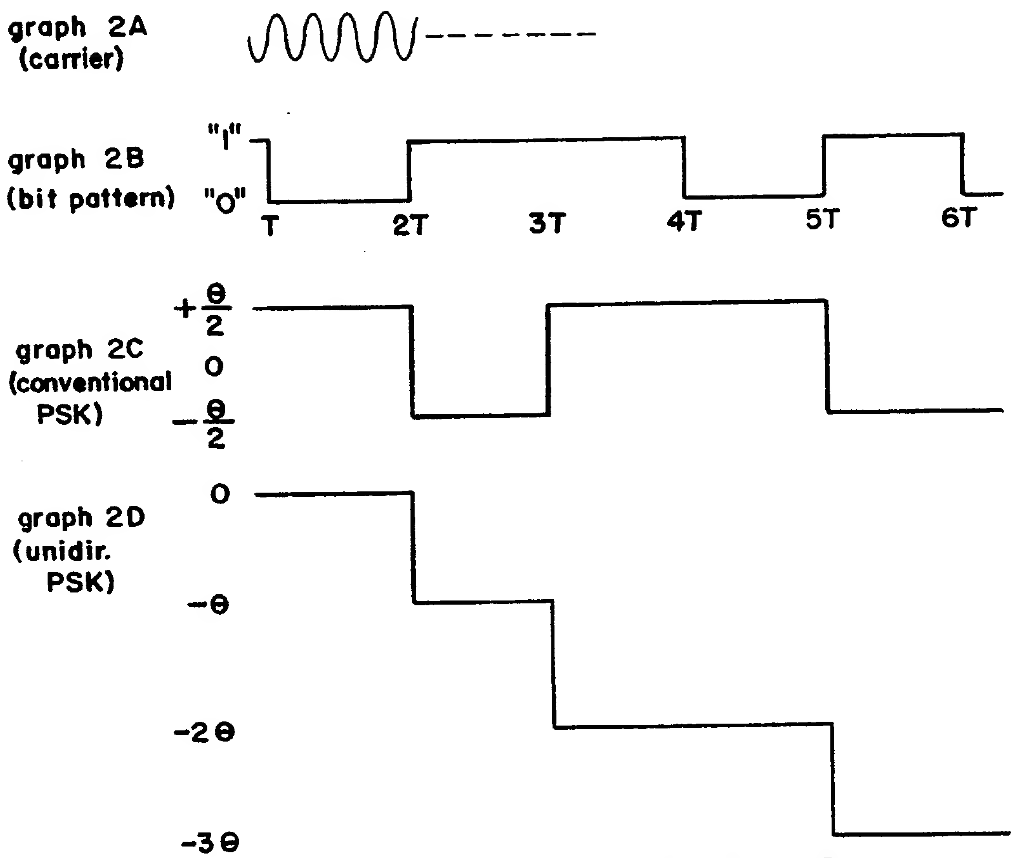

FIG. 2

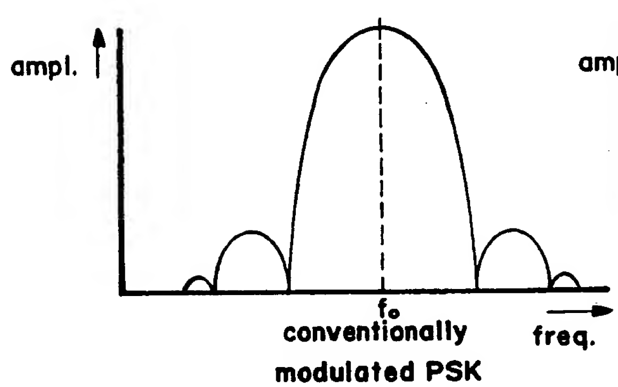

FIG. 6A

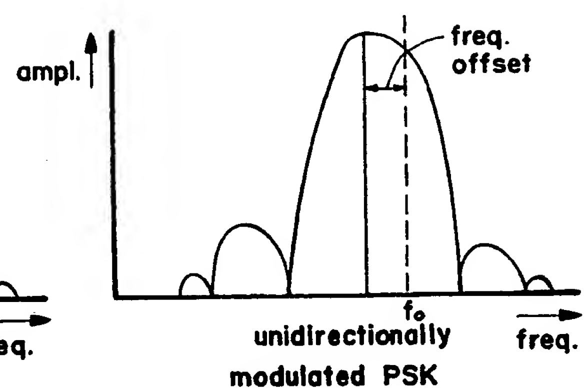

FIG. 6B

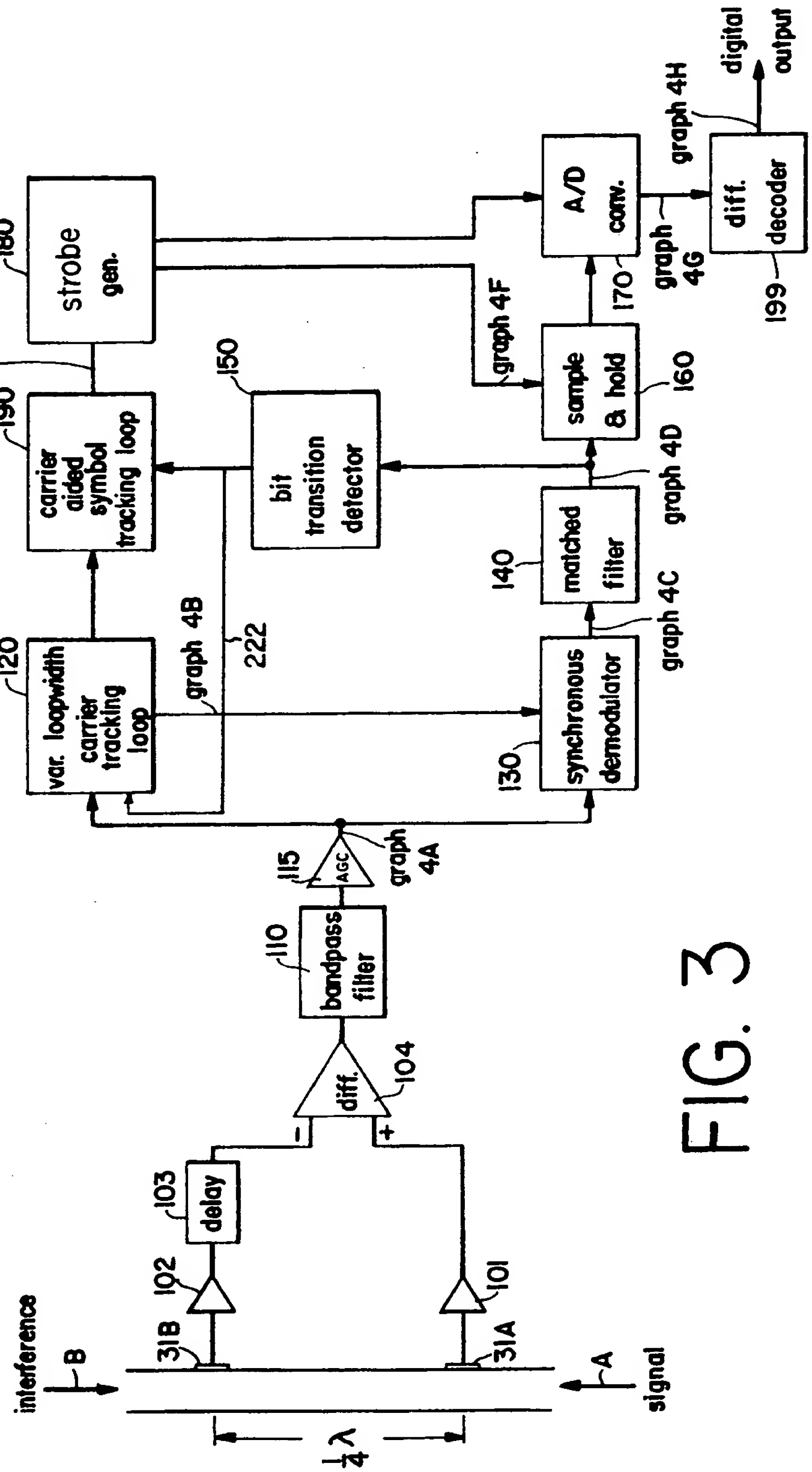
interference
B
31B
102
103
delay
101
31A
A
signal
$\frac{1}{4}\lambda$
-
+
diff.
104
110
bandpass filter
115
AGC
graph 4A
120
var. loopwidth carrier tracking loop
graph 4B
222
130
synchronous demodulator
graph 4C
140
matched filter
graph 4D
150
bit transition detector
190
carrier aided symbol tracking loop
graph 4E
180
strobe gen.
graph 4F
160
sample & hold
170
A/D conv.
graph 4G
199
diff. decoder
graph 4H
digital output

FIG. 3

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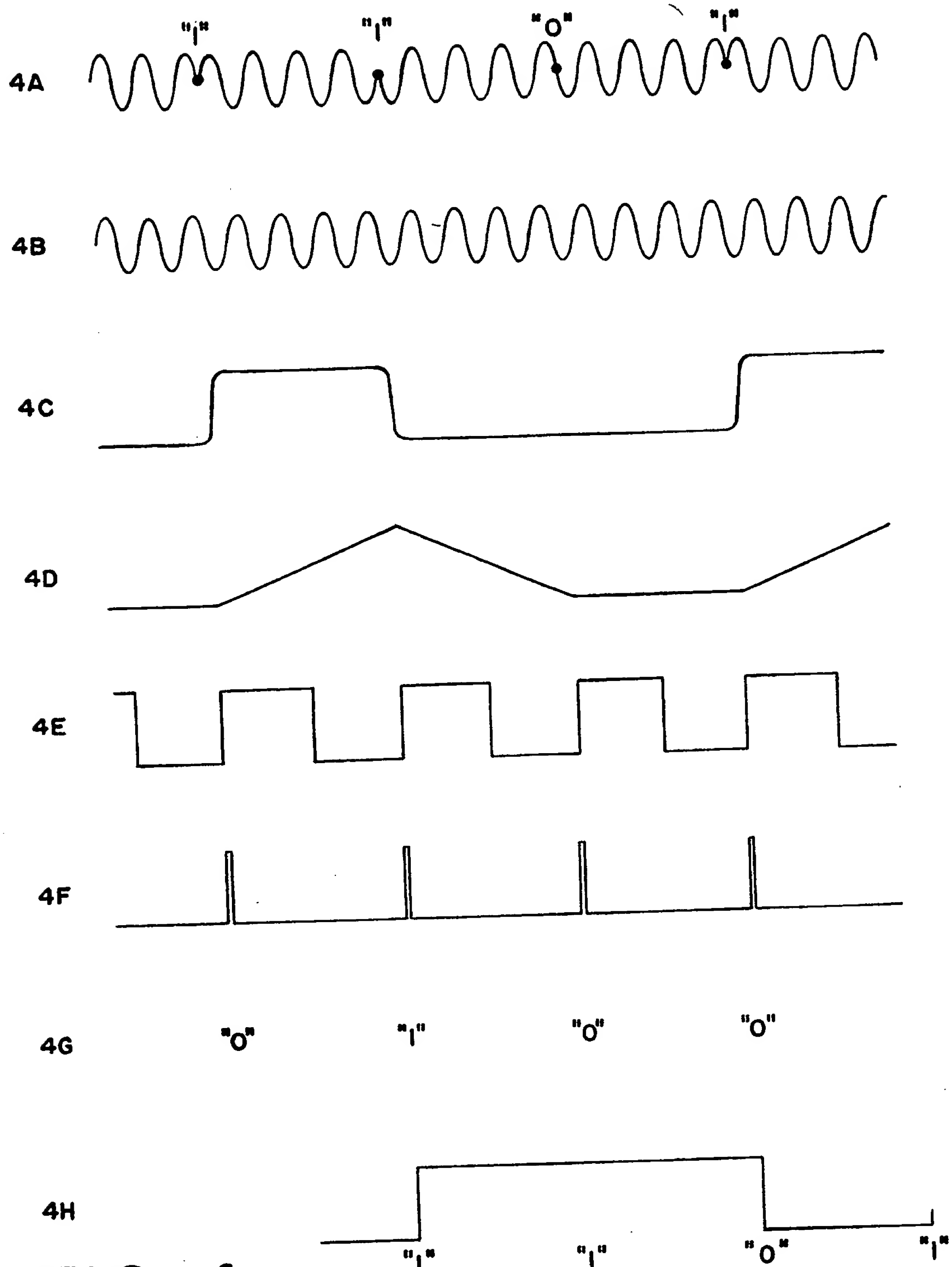


FIG. 4

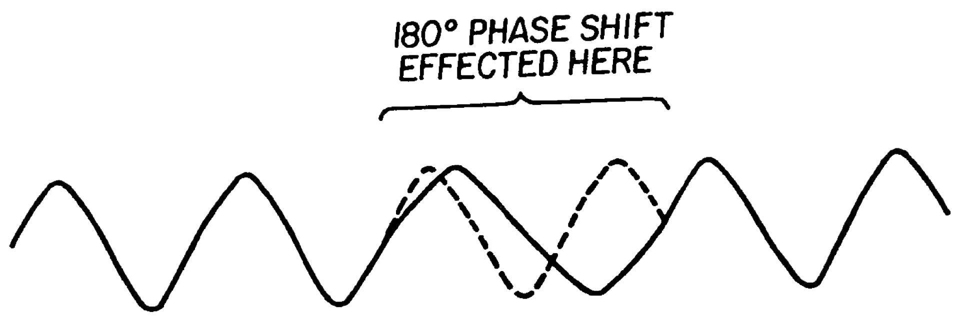

180° PHASE SHIFT
EFFECTED HERE

FIG.5

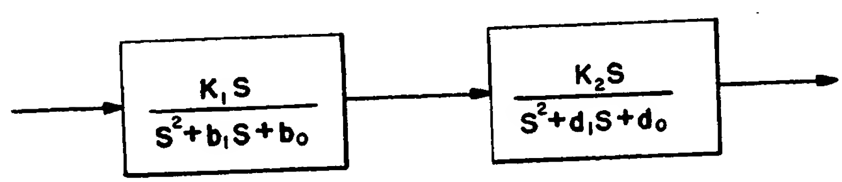

$\frac{K_1 S}{S^2+b_1 S+b_0}$
$\frac{K_2 S}{S^2+d_1 S+d_0}$

FIG. 7

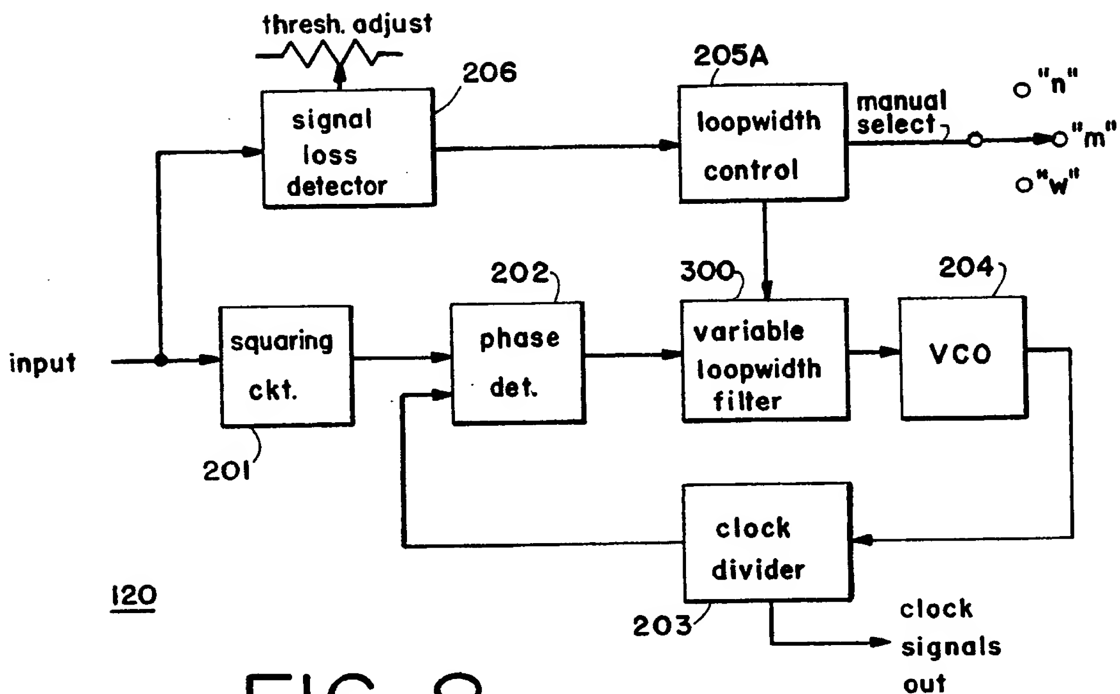

thresh. adjust
206
205A
signal loss detector
loopwidth control
manual select
"n"
"m"
"w"
202
300
204
input
squaring ckt.
phase det.
variable loopwidth filter
VCO
201
clock divider
120
203
clock signals out

FIG. 8

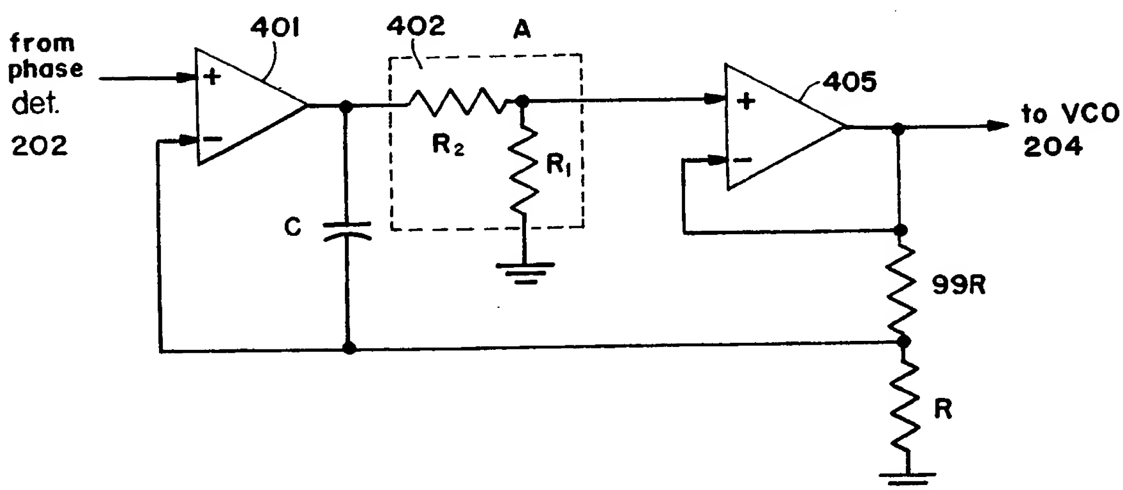
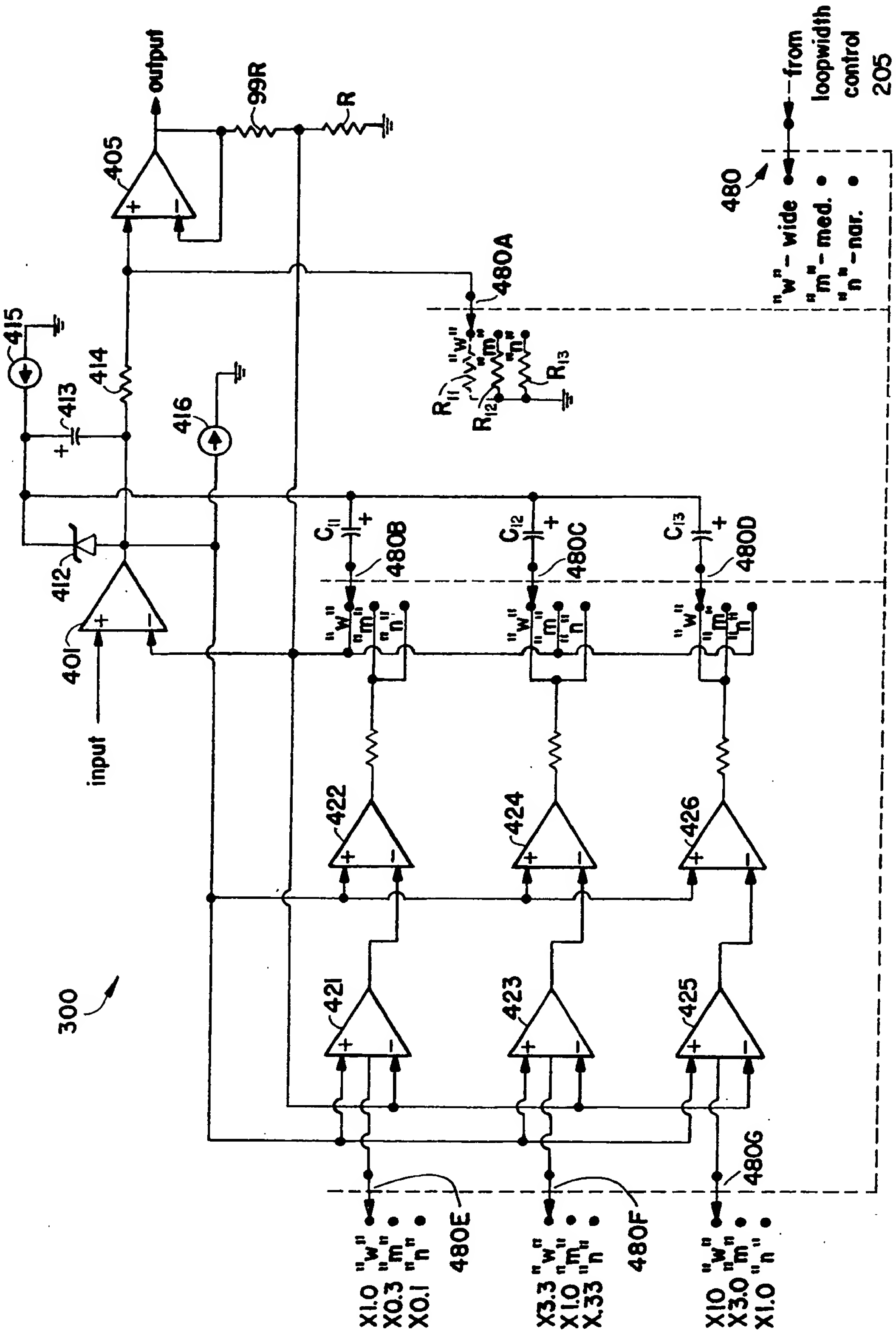

from phase det. 202
401
402
A
405
to VCO 204
R2
R1
C
99R
R

FIG. 9



300
input
401
412
413
414
415
416
405
output
99R
R
480
480A
480B
480C
480D
480E
480F
480G
R_{11}
R_{12}
R_{13}
C_{11}
C_{12}
C_{13}
421
422
423
424
425
426
"w" - wide
"m" - med.
"n" - nar.
from loopwidth control 205
X1.0 "w"
X0.3 "m"
X0.1 "n"
X3.3 "w"
X1.0 "m"
X.33 "n"
X10 "w"
X3.0 "m"
X1.0 "n"

FIG. 10

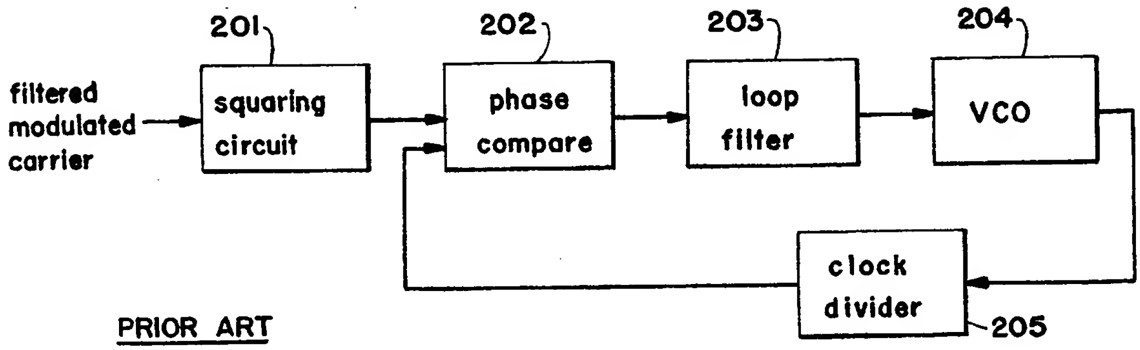


FIG. 11

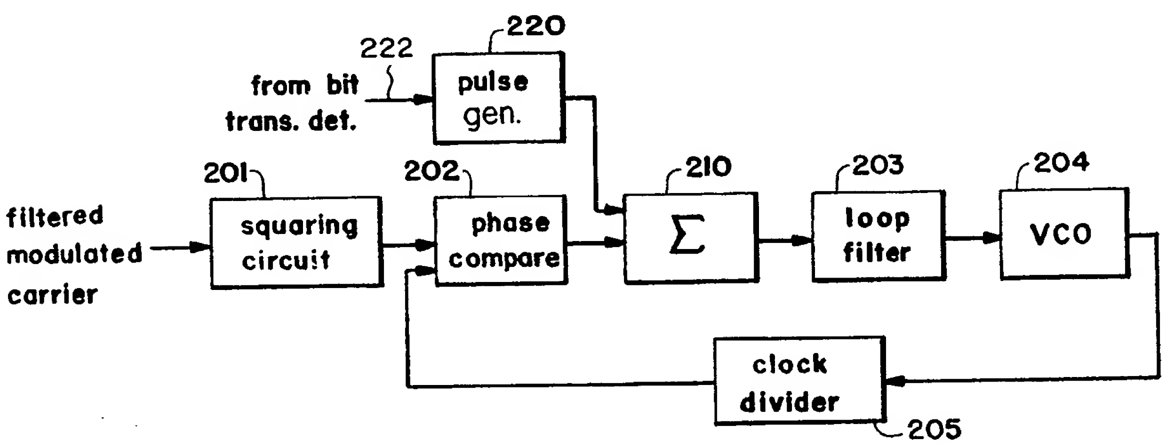


FIG. 12

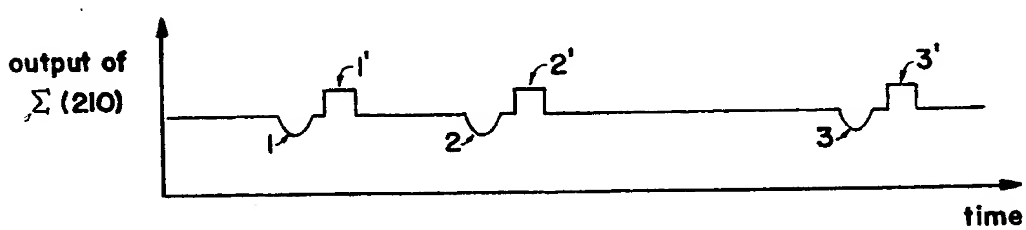


FIG. 13

SPECIFICATION

Method and apparatus for demodulating signals in a logging-while-drilling system

This invention relates to communication systems and, more particularly, to improved apparatus and methods for receiving and interpreting data signals being telemetered to the surface of the earth in a logging-while-drilling system.

Logging-while-drilling involves the transmission to the earth's surface of downhole measurements taken during drilling, the measurements generally being taken by instruments mounted just behind the drill bit. The prospect of continuously obtaining information during drilling with the entire string in place is clearly attractive. Nonetheless, logging-while-drilling systems have not yet achieved widespread commercial acceptance, largely due to problems associated with transmitting the measured information through the noisy and hostile environment of a borehole. Various schemes have been proposed for achieving transmission of measurement information to the earth's surface. For example, one proposed technique would transmit logging measurements by means of insulated electrical conductors extending through the drill string. This scheme, however, requires adaptation of drill string pipes including provision for electrical connections at the drill pipe couplings. Another proposed scheme employs an acoustic wave which would travel upward through the metal drill string, but the obvious high levels of interfering noise in a drill string are a problem in this technique. Another scheme, which appears particularly promising, utilizes a drilling fluid within the borehole as a transmission medium for acoustic waves modulated with the measurement information. Typically, drilling fluid or "mud" is circulated downward through the drill string and drill bit and upward through the annulus defined by the portion of the borehole surrounding the drill string. This is conventionally done to remove drill cuttings and maintain a desired hydrostatic pressure in the borehole. In the technique referred to, a downhole acoustic transmitter, known as a rotary valve or "mud siren", repeatedly interrupts the flow of the drilling fluid, and this causes an acoustic carrier signal to be generated in the drilling fluid at a frequency which depends upon the rate of interruption. The acoustic carrier is modulated as a function of downhole digital logging data. In a phase shift keying ("PSK") modulating technique, the acoustic carrier is modulated between two (or more) phase states. Various coding schemes are possible using PSK modulation. In a "non-return to zero" coding scheme, a change in phase represents a particular binary state (for example, a logical "1"), whereas the absence of a change of phase represents the other binary state (for example, a logical "0"). The phase changes are achieved mechanically by temporarily modifying the interruption frequency of the mud siren to a higher or lower frequency until a desired phase lag (or lead) is achieved, and then returning the mud siren to its nominal frequency. For example, if the nominal frequency of the mud siren is 12Hz., a phase change of 180° can be obtained by temporarily lowering the frequency of the mud siren to 8Hz. for 125 milliseconds (which is one period at 8Hz. and one and one-half periods at 12Hz.) and then restoring the mud siren frequency to 12Hz. It is readily seen that a 180° phase shift could also be achieved by temporarily increasing the mud siren frequency for an appropriate period of time (i.e., to obtain a desired phase lead), and then returning to the nominal frequency.

In conventional (PSK) communications, the carrier phase is conventionally changed in alternate directions (that is, alternating lead and lag) so that the net change in carrier phase over a long period of time is close to zero. In a logging-while-drilling system wherein an electromechanical device, such as a mud siren, is employed to impart acoustic waves to the drilling fluid, it is preferable to effect all phase changes in the same direction (i.e. either all lags or all leads) which results in the technique for driving the mud siren being more efficient and straightforward. (For example, if all phase changes are achieved by momentary decreases in frequency, it is never necessary to increase the frequency above the nominal frequency, and less drive power is needed for the mud siren. Also, the control circuitry can be less complex.) The term "unidirectional" PSK modulation means this type of modulation wherein all phase changes are in the same direction.

The modulated acoustic signal is received uphole by one or more transducers which convert the acoustic signal to an electrical signal. It is then necessary to recover the digital information which is contained in the modulation of the received signal. Briefly, this is achieved by first processing the received signals to extract the carrier signal. The reconstructed carrier is then used to synchronously demodulate the modulated electrical signal.

In the conventional type of system described, a bandpass filter is typically employed at the receiver, the filter having a bandpass spectrum centered at the nominal carrier frequency and being used to detect the modulated carrier. As part of the present invention it has been discovered, however, that employment of a filter centered at the nominal carrier frequency results in less than optimum performance. In particular, the unidirectional nature of the modulation results in the average carrier frequency being different from the nominal carrier frequency. It has also been recog-

nized that a further problem occurs with using conventional existing filters in phase shift keying systems of the type described. A typical conventional filter design strives to attain a symmetrical spectral characteristic about the filter center frequency. However, the unidirectional nature of the modulation results in a symmetrical filter characteristic being a less than optimum match with the frequency characteristic of the transmitted signal.

It is an object of an aspect of the present invention to provide an improved filter for use in detection in a phase shift keying transmission system of the type wherein modulation is achieved by temporary unidirectional modification of carrier frequency.

In the known type of system described, a carrier tracking loop is typically employed at the receiver, the purpose of the tracking loop being to lock onto the carrier of the received signals and to produce timing signals that can be used in the demodulation process. It is desirable to acquire a locking onto the carrier as quickly as possible so as to avoid possible loss of information. It is also desirable, once lock is achieved, to have a tracking loop which will be relatively stable, i.e. not adversely affected by short term error component signals in the loop at various frequencies. These two objectives are somewhat at odds, since relatively fast acquisition of lock requires a relatively wide loopwidth whereas stability of the loop would generally dictate a relatively narrow loopwidth. It is known that loopwidth can be manually varied once lock has been achieved, but this technique is not particularly convenient. Also, in the type of logging-while drilling apparatus described above, where relatively low frequency acoustic signals are employed, practical problems arise when attempting to vary the loopwidth of the carrier tracking loop. In particular, the varying of loopwidth generally involves the switching of different capacitors into the loop filter circuit and, at the same time, modifying the loop gain factor. At the frequencies of interest, the capacitors in the circuit generally have relatively large values and are implemented using electrolytic capacitors which provide relatively large capacitance without the undue size which is typical of non-electrolytic capacitors. When a previously inactive capacitor is switched into the circuit, a problem arises due to introduction of an offset voltage which results from the previous voltage across the new capacitor not corresponding to the voltage applied thereacross once it is switched into the circuit.

It is an object of another aspect of the present invention to provide an improved variable loopwidth carrier tracking loop which may overcome prior art problems of the type set forth.

In the known type of system described, the carrier is generally extracted using a carrier tracking loop circuit. The carrier tracking loop is a phase-locked loop that includes a voltage controlled oscillator ("VCO") which is responsive to error signals resulting from differences between the phase of the signal derived from the VCO and the phase of the carrier signal. In accordance with the present invention, it has been discovered, however, that the unidirectional nature of the phase modulation in the type of system described above tends to cause a problem in operation of the phase locked loop. In particular, since phase changes are implemented by momentary variation of frequency, error pulses are generated in the phase-locked loop each time a data transition occurs. Since the PSK modulation is unidirectional (i.e., momentary frequency modification is always to a lower frequency or always to a higher frequency) these error pulses always have the same polarity. These error pulses can tend to cause undesirable frequency deviations in the carrier tracking loop.

It is a further aspect of the object of the present invention to provide an improved carrier tracking loop for use in detection in a phase shift keying transmission system of the type wherein modulation is achieved by temporary unidirectional modification of carrier frequency.

One aspect of the present invention is directed to a method utilizing a PSK signal that has been modulated with digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; comprising the steps of: filtering the modulated carrier signal with a filter having a bandpass center frequency which is offset from the nominal carrier frequency in the direction of said unidirectional decrease or increase of frequency; and recovering the digital information from the filtered signal.

Another aspect of the present invention is directed to a method utilizing a PSK signal that has been modulated with digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; comprising the steps of: filtering the modulated carrier signal with a filter having a bandpass characteristic which is skewed in the direction of said unidirectional decrease or increase of frequency; and recovering the digital information from the filtered signal.

A further aspect of the present invention is directed to a method for reducing transient signals that result from switching a different capacitor into a circuit for use in an electronic system which includes: a pair of terminals; a plurality of capacitors, each of said capacitors having one of its plates coupled to one of said terminals; switching means for coupling the

other plate of a selected one of said capacitors to the other terminal; and variable gain means synchronized with said switching means and affecting the potential of said other terminal; characterized by: continuously generating a reference voltage associated with each of said plurality of capacitors not presently coupled between said pair of terminals, each said generated reference voltage being a function of the voltage which would appear across its associated capacitor in the event said associated capacitor were instantaneously switched by said switching means between said pair of terminals; and continuously applying each said generated reference voltage across its associated capacitor.

Still another aspect of the present invention is directed to a method of stabilizing a carrier tracking loop used in conjunction with an apparatus which receives a PSK signal that was modulated with digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; said apparatus including a carrier tracking loop circuit for tracking the carrier of the received signal, said carrier tracking loop circuit including a controlled oscillator having a control terminal, the frequency of said oscillator being determined by a signal applied to said control terminal, a comparator for generating a control signal by comparing the phase of a signal derived from the received PSK modulated signal to the phase of a signal derived from the output of said controlled oscillator, and means for applying said control signal to the control terminal of said oscillator; said method comprising the steps of: generating compensating pulses in response to transitions in the received signal; and applying said compensating pulses to said control terminal to account for the difference between the nominal frequency of said carrier and the average frequency of the received signal which result from the unidirectional nature of the carrier modulation.

The present invention also includes another aspect directed to an apparatus which receives a PSK signal modulated with digital information and is operative to recover the digital information therefrom, said PSK modulated signal having been modulated with the digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; said apparatus including a filter for use in selectively filtering the modulated carrier signal; characterized by said filter having a bandpass center frequency which is offset from the nominal carrier frequency in the direction of said unidirectional decrease or increase of frequency.

The present invention includes a further aspect directed to an apparatus for demodulating a digital signal which receives a PSK signal modulated with digital information and is operative to recover the digital information therefrom, said PSK modulated signal having been modulated with the digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; and then returning the carrier to nominal frequency once the phase change has been effected; said apparatus including a filter for use in selectively filtering the modulated carrier signal; characterized by said filter having a bandpass characteristic which is skewed in the direction of said unidirectional decrease or increase of frequency.

A further aspect of the present invention is directed to an electronic system which includes: a pair of terminals; a plurality of capacitors, each of said capacitors having one of its plates coupled to one of said terminals; switching means for coupling the other plate of a selected one of said capacitors to the other terminal; and variable gain means synchronized with said switching means and affecting the potential of said other terminal; characterized by a circuit for reducing transient signals that result from switching a different capacitor between said pair of terminals, comprising:

means for continuously generating a reference voltage associated with each of said plurality of capacitors not presently coupled between said pair of terminals, each said generated reference voltage being a function of the voltage which would appear across its associated capacitor in the event said associated capacitor were instantaneously switched by said switching means between said pair of terminals; and

means for continuously applying each said generated reference voltage across its associated capacitor.

A still further aspect of the present invention is directed to a variable loopwidth carrier tracking loop for locking onto the carrier of an input signal, comprising:

a phase-locked loop including an oscillator having a control input, error signal generating means for generating an error signal as a function of the phase difference between a signal derived from said oscillator and the input signal, and a variable filter having a plurality of different bandwidths for coupling the output of said error signal generating means to the control input of said oscillator; and characterized by:

loopwidth control means coupled to said variable filter for automatically changing the loopwidth of said filter as a function of the input signal.

Figure 1 is a simplified schematic diagram of a logging-while-drilling apparatus which includes the present invention.

Figure 2 includes graphs which illustrate conventional PSK modulation and unidirectional ramp phase PSK modulation utilized in the present invention.

Figure 3 is a block diagram of the uphole receiving subsystem of the Fig. 1 apparatus.

Figure 4 illustrates idealized waveforms useful in understanding the nature of signals which appear at various locations of the receiving subsystem circuitry of Fig. 3.

Figure 5 illustrates the nature of a phase change as implemented in accordance with the PSK modulation of Fig. 2.

Figure 6 illustrates the nature of the frequency spectrum of a conventional PSK modulated signal as compared to the spectrum of a unidirectional PSK modulated signal.

Figure 7 illustrates an example of a filter which is useful in the present invention.

Figure 8 is a block diagram of a variable loopwidth phase-locked loop in accordance with an embodiment of the invention.

Figure 9 illustrates a basic loop filter.

Figure 10 illustrates a variable loopwidth filter in accordance with an embodiment of the invention.

Figure 11 illustrates a prior art carrier tracking loop.

Figure 12 illustrates an embodiment of an improved carrier tracking loop in accordance with an aspect of the invention.

Figure 13 illustrates the type of waveform produced which is input to the loop filter of the carrier tracking loop of Fig. 11.

Referring to Fig. 1, there is illustrated a simplified diagram of a logging-while-drilling apparatus in accordance with an embodiment of the present invention, as used in conjunction with a conventional drilling apparatus. A platform and derrick 10 are positioned over a borehole 11 that is formed in the earth by rotary drilling. A drill string 12 is suspended within the borehole and includes a drill bit 15 at its lower end. The drill string 12, and the drill 15 attached thereto, is rotated by a rotating table 16 (energized by means not shown) which engages a kelly 17 at the upper end of the drill string. The drill string is suspended from a hook 18 attached to a travelling block (not shown). The kelly is connected to the hook through a rotary swivel 19 which permits rotation of the drill string relative to the hook. Drilling fluid or mud 26 is contained in a pit 27 in the earth. A pump 29 pumps the drilling fluid into the drill string via a port in the swivel 19 to flow downward through the center of drill string 12. The drilling fluid exits the drill string via ports in the drill bit 15 and then circulates upward in the region between the outside of the drill string and the periphery of the borehole. As is well known, the drilling fluid thereby carries formation cuttings to the surface of the earth, and the drilling fluid is returned to the pit 27 for recirculation. The small arrows in Fig. 1 illustrate the typical direction of flow of the drilling fluid.

Mounted within the drill string 12, preferably near the drill bit 15, is a downhole sensing and transmitting subsystem 50. Subsystem 50 includes a measuring apparatus 55 which may measure any desired downhole condition, for example resistivity, gamma ray, weight on bit, tool face angle, etc. It will be understood, however, that the measuring apparatus 55 can be employed to measure any useful downhole parameter. The transmitting portion of the downhole subsystem includes an acoustic transmitter 56 which generates an acoustic signal in the drilling fluid that is representative of the measured downhole conditions. One suitable type of acoustic transmitter, which is known in the art, employs a device known as a "mud siren" which includes a slotted stator and a slotted rotor that rotates and repeatedly interrupts the flow of drilling fluid to establish a desired acoustic wave signal in the drilling fluid. Transmitter 56 is controlled by transmitter control and driving electronics 57 which includes analog-to-digital (A/D) circuitry that converts the signals representative of downhole conditions into digital form. The control and driving electronics 57 also includes a phase shift keying (PSK) modulator which produces driving signals for application to the transmitter 56.

In conventional phase shift keyed (PSK) communications, the phase of a carrier signal is changed in accordance with a digital data signal having two or more levels to produce a modulated carrier having two or more phases. The carrier phase is conventionally changed in alternate directions (that is, alternating lead and lag) so that the net change in carrier phase over a long period of time is close to zero. In a logging-while-drilling system wherein an electromechanical device, such as a mud siren, is employed to impart acoustic waves to the drilling fluid, it is preferable to effect all phase changes in the same direction (i.e. either all lags or all leads) which results in the technique for driving the mud siren being more efficient and straightforward. As used herein, the term "unidirectional" PSK modulation is intended to mean this type of modulation wherein all phase changes are in the same direction. Techniques for driving a mud siren to obtain a PSK modulated acoustic carrier wave in drilling fluid, and to obtain unidirectional PSK modulation thereof, are disclosed, for example, in the U. S. Patents No.s 3,789,355 and 3,820,063. It will be understood, however, that any suitable means can be employed for obtaining the types of unidirectional PSK modulation described herein. Fig. 2 illustrates the difference between conventional PSK modulation and the unidirectional PSK modulation utilized in a logging-while-drilling system. Graph 2A illustrates an

unmodulated carrier signal having a period of T/4 where T is the bit period of the modulating information. An exemplary bit pattern is shown in graph 2B, with "0" to "1" transitions occurring at times 2T and 5T, and "1" to "0" transitions occurring at times T, 4T, and 6T. If a conventional "differentially encoded PSK" coding scheme is employed, a phase change at the bit time epoch (T, 2T, 3 4T . . .) is indicative of a "1" bit, whereas the absence of a phase change at the bit time epoch is indicative of a "0" bit. It will be understood, however, that the opposite convention can be employed, or that any suitable coding scheme could be employed, consistent with the present invention. Accordingly, in graph 2C where conventional PSK modulation is illustrated, a phase change of θ is implemented each time the next bit is a "1", which means that phase changes are effected at times 2T, 3T and 5T. Thus, graph 2C shows phase changes as being effected at these times, with the phase changes alternating in direction. Graph 2D illustrates the nature of the PSK modulation in an unidirectional PSK modulation as used herein. Phase changes are seen to be effected at the same places, but in this illustrative example each phase change is negative (i.e. resulting in a phase lag) and the phase changes are seen to accumulate.

Referring again to Fig. 1, the generated acoustic wave (i.e., the primary component thereof to be received) travels upward in the fluid through the center of the drill string at the speed of sound in the fluid. The acoustic wave is received at the surface of the earth, by transducers represented by reference numeral 31. The transducers, which may for example be piezoelectric transducers, convert the received acoustic signals to electronic signals. The output of the transducer 31 is coupled to the uphole receiving subsystem 100 which is operative to demodulate the transmitted signals and display the downhole measurement information on display and/or recorder 500.

Referring to Fig. 3, there is shown a block diagram of the uphole receiving subsystem which includes an improved filter in accordance with one aspect of the invention. The waveforms of Fig. 4, which show an exemplary bit pattern "1011" will be referred to from time to time to illustrate operation. The acoustic signals in the borehole fluid are sensed by transducers 31 (Fig. 1) which, in the present embodiment comprises transducers 31A and 31B. In the present embodiment, this pair of transducers is utilized in conjunction with a differential detection arrangement that includes delay 103 and difference amplifier 104. The output of transducer 31B is coupled, via buffer amplifier 102 and delay 103, to the negative input terminal of the difference amplifier 104. The transducer 31A is coupled, via buffer amplifier 101, to the positive input terminal of difference amplifier 104. This differential detector arrangement is employed for the purpose of rejecting noise traveling in a direction of propagation that is opposed to that of the primary acoustic carrier wave. For example, if the distance between transducers 31A and 31B is selected as being a quarter wavelength at the carrier frequency, and the delay 103 is also set at a quarter wavelength at the carrier frequency, acoustic waves traveling in the direction of the primary signal (arrow A) will experience a total of one-half wavelength of phase retardation. When the output of delay 103 is subtracted from the undelayed signal from transducer 31A, signals traveling in the direction of arrow A are seen to add in phase. However, acoustic signals traveling in the opposite direction (arrow B) will result in inputs to the differential amplifier 104 that are in phase, thereby resulting in the cancellation of these signals. This is readily seen by recognizing that, in such case, the input to the positive input terminal of differential amplifier 104 experiences a quarter wavelength delay due to the transducer spacing, whereas the input to the negative input terminal of the differential amplifier 104 experiences a quarter wavelength delay due to the electrical delay 103.

The output of differential amplifier 104 is coupled to a bandpass filter 110 which has a filter characteristic in accordance with the principles of one aspect of the present invention and which will be described in further detail hereinbelow.

The output of filter 110 is coupled to an automatic gain control (AGC) amplifier 115 which is provided with a fast-attack slow-release characteristic. The fast-attack mode is useful in achieving stability and sync lock in a minimum time, and the slow release mode maintains the gain during momentary loss or level change of signal. The output of AGC amplifier 115 (shown in idealized form in graph 4A) is coupled to both a synchronous demodulator 130 and variable loopwidth carrier tracking loop 120. The variable loopwidth carrier tracking loop 120 may comprise a phase-locked loop and is another important aspect of the present invention. The variable loopwidth can be operated in either a manual or an automatic mode. In the manual mode of operation, the carrier tracking loop will operate in a particular fixed loopwidth (for example, wide, medium or narrow) in accordance with operator selection. These loopwidths may be, for example, 0.3 Hz, 0.1 Hz and 0.03 Hz, respectively, covering a ten to one range. The wide or medium loopwidth will typically be utilized when acquiring lock, and the narrow loopwidth will be switched in once lock has been acquired, so as to enhance the loop stability. In the automatic mode of operation, the loop will initially acquire synchronization using the widest loopwidth (or the medium

loopwidth, if so desired under certain conditions). After acquiring synchronization, the loopwidth is switched to a narrower value. When a signal loss occurs, as indicated by an output from a signal loss detector in the circuit 120, the loopwidth is again switched to its widest setting. In either the manual or automatic mode of operation, the variable loopwidth carrier tracking loop may be provided with circuitry for precharging certain capacitors therein which are switched into and out of operation when switching loopwidths. This capacitor precharging technique is advantageous in preventing possible loss of lock when, for example, switching to a narrower loopwidth, as might be caused by transient voltages resulting from the initial voltages across capacitors that are switched into operation in the circuit. Further details on the variable loopwidth carrier tracking loop are provided below.

As discussed in greater detail below, the output of the variable loopwdith carrier tracking loop circuit 120 is derived from the output of a voltage controlled oscillator (VCO) in the phase locked loop of the circuit. This oscillator typically operates at a multiple of the nominal carrier frequency. A clock generator, which includes a frequency divider, therefore derives a clock signal from this VCO output, the derived clock signal (which is illustrated in graph 4B) being at the carrier frequency and in a form suitable for use in demodulating the filtered input signal. The clock generator in circuit 120 may include clock correction circuitry in accordance with a further aspect of the present invention. As described in detail below, the unidirectional nature of the PSK modulated carrier signal results in a buildup of error signal components in the carrier tracking loop. If not accounted for, such as by using clock correction circuitry as described below, the buildup of error component signals can cause an undesirable drift of the voltage controlled oscillator in the carrier tracking loop. This undesirable buildup of error components can be eliminated by providing offsetting pulses which tend to cancel the error signals that would otherwise accumulate. Since the type of error signals under consideration occur at each bit transition, the output of a bit transition detector 150 (to be described further hereinbelow) is used to regulate the generation of correction pulses.

The output of the carrier tracking loop circuit 120 (graph 4B) is coupled to the synchronous demodulator 130 which, as noted above, receives as its other input the output of AGC amplifier 115 which is to be demodulated. The synchronous demodulator may be, for example, an analog multiplier. Its demodulated output is illustrated by the waveform of graph 4C. The output of the synchronous demodulator 130 is coupled to a matched filter 140. The filter 140 is matched to a square pulse at the bit rate. As is known in the art, the matched filter is operative, upon a data transition at its input, to integrate for a time equal to one bit period. Accordingly, at the end of each bit period, the output of the matched filter is at an extreme positive or negative value (waveform of graph 4D) at which sampling can be most efficiently achieved. Sampling of the output of matched filter 140 is performed by a sample and hold circuit 160 whose output is coupled to an analog-to-digital converter 170 that generates a signal in digital form. (The output of match filter 140 is also coupled to bit transition detector 150, which may include a zero crossing detector that senses zero crossings of the matched filter output to produce output pulses having a phase which is synchronized with the bit transitions. Use of the transition detector output is referred to directly hereinbelow.) The signal utilized to trigger sampling by the sample and hold circuit 160 and to define the conversion period of the analog-to-digital converter 170 is generated by a strobe generator 180. The sampling signal produced by the strobe generator (waveform of graph 4F) is seen to be at the bit or symbol rate. To obtain this relatively accurate signal at the bit rate, a carrier-aided symbol tracking loop 190 may be employed. The carrier-aided symbol tracking loop is described in the U. S. Patent Application Serial No. 684,604. Briefly, the circuit 190 is a squaring type of phase-locked loop which includes a voltage controlled oscillator and a frequency divider in the loop. In this respect, the circuit is like a conventional bit synchronizer. However, as described in the referenced U. S. patent application, in addition to the tracking loop receiving timing information when a transition is detected in the received signal (i.e., the output of bit transition detector 150 in Fig. 3), the output of the carrier tracking loop 120 is also used to aid the symbol tracking loop 190 (output illustrated in graph 4E) during those periods where symbol transitions are absent. This is made possible by the coherent relationship between the carrier and bit rates. If after a number of bit periods there are no bit transitions, a signal derived from the carrier is used to maintain synchronization.

The bit pattern output of A/D converter 170, for this example, is illustrated in graph 4G, and can be seen to result from the sampling of the matched filter output (graph 4D) with the strobe signal (graph 4F) and subsequent A/D conversion. Since the data was originally encoded in conventional "differential encoded PSK" form (as described above), a differential decoder 199 is employed to recover the data in its original form. In particular, since a change in phase was indicative of a "1" in the encoding scheme, a bit change in the output of A/D converter 170 (graph 4G) is interpreted as a "1" by the

differential decoder 199. Conversely, the absence of a bit change in the A/D converter output is interpreted as a "0". Accordingly, and as is known in the art, the differential decoder includes an exclusive-OR gate which operates on successively received bits and generates a "1" output when successive bits are different and a "0" output when successive bits are the same. The output of differential decoder 199 is illustrated in Fig. 4H for the present example.

It will be understood that in the graph 4A of Fig. 4, the PSK modulation was illustrated in idealized form, with "instantaneous" phase changes, to facilitate understanding of operation of the system of Fig. 3. The actual phase changes are implemented in the manner illustrated in conjunction with graph 2D. Fig. 5 illustrates such a phase change, effected by momentary lowering of the carrier frequency until the desired phase shift is achieved. The dashed line shows what the carrier waveform would look like without the frequency modification.

In an embodiment of the present invention, the carrier frequency is 12 Hz and the bit rate is 1.5 Hz. Unidirectional PSK modulation is implemented by momentarily lowering the carrier frequency to 8 Hz until a 180° phase lag has been achieved, and then restoring the carrier to its nominal 12 Hz frequency. (The desired lag is one-half the period of the nominal carrier frequency. A frequency of 8 Hz has a period which is $1\frac{1}{2}$ times the period of the nominal carrier frequency. Accordingly, after one full cycle at 8 Hz (125 millisec.) the desired phase lag will be obtained. This is readily seen from Fig. 5 wherein the solid line waveform changes to 8Hz for one cycle while the dashed line waveform illustrates continuation at a 12 Hz frequency. However, since it takes a finite time to change between the two frequencies—and during the transition the average frequency is less than 12 Hz—the actual time spent at 8 Hz is slightly less than 125 ms.) Techniques for driving the mud siren in this manner are known in the art, e.g. in the above-referenced U. S. Patent No.s, 3,789,355 and 3,820,063.

Having described the overall receiver subsystem, details of certain of its aspects in accordance with the present invention will now be set forth in greater detail. In accordance with one aspect of the present invention, it has been noted that the unidirectional phase shifting of the carrier causes the modulated signal spectrum to be shifted in frequency from the nominal carrier frequency. The frequency shift, or offset, is accompanied by an asymmetry, or skewing, in the spectrum. Fig. 6B illustrates the nature of the unidirectional PSK frequency spectrum, and can be compared to the frequency spectrum of a conventional PSK modulated signal having the same nominal carrier frequency, f_0. The use of a bandpass filter (e.g. filter 110 of Fig. 3) which takes account of this offset and a symmetry of the frequency spectrum of the modulated signal, is advantageous in more efficiently separating the signal from the noise and minimizing distortion of the signal by the filter. The precise degree of spectrum offset and asymmetry depends upon the data pattern of the modulation. For example, an alternating "1", "0" data pattern would result in an offset by an amount equal to about the bit rate. Any other data pattern would result in an offset of somewhat less than the bit rate. If the data pattern is not known a priori (as is generally the case), a random data pattern can be assumed and such a pattern results in an offset from the carrier frequency of approximately one-half the bit rate. For example, in the present embodiment wherein the carrier is at 12 Hz, the bit rate is at 1.5 Hz, and wherein PSK modulation is achieved by unidirectional momentary decreasing of frequency, the preferred filter center frequency of the bandpass filter would be at 11.25 Hz; i.e., the nominal carrier frequency minus half the bit rate. (It will be understood that if phase shifting were achieved by unidirectional momentary increases in frequency, the offset would be toward the higher frequencies and would lie at 12.75 Hz for such case.)

Consistent with principles of the present invention, there are various ways in which the bandpass filter can be designed. The bandwidth of the filter is chosen to pass the modulated signal with a minimum of distortion while suppressing spurious noise and interference. The minimum bandwidth ($-$3dB to $-$3dB) for filtering in a PSK system is typically equal to the bit rate, although a somewhat wider bandwidth, for example of 1.5 times the bit rate, is generally recommended. In designing the bandpass filter, the following steps can be followed: First, a low pass filter prototype is selected and it is scaled to have a bandwidth equal to one-half of the desired bandpass filter bandwidth. The low pass filter design is next translated to a bandpass filter centered at a frequency which is offset from the carrier frequency in accordance with the rules set forth above. The bandpass filter transfer zeros are then selected to provide the desired filter symmetry (or asymmetry) characteristics. A particular filter configuration is then adopted and the filter component values therefor are computed. Since the details of how such a design can be implemented are believed to be within the ordinary capability of one skilled in the art, in the interest of brevity no such details are supplied.

An exemplary filter can be realized using a cascade of two active RC biquadratic filter sections. A feedforward circuit configuration as described in "Design Formulas for Biquad Active Filters Using Three Operational Ampli-

fiers'', by Fleischer & Tow, Proc. of the IEEE, May 1973, can be used. The final filter can be composed of the two cascaded active RC biquad sections, as represented by the transfer functions of Fig. 7, with

$$b_1 = 20.764 = d_1$$
$$b_0 = 5987.63$$
$$d_0 = 4292.79$$
$$K_1 = K_2 = \sqrt{K}$$

for the first biquad filter section. The design formulae of Fleischer & Tow may be used to compute the values of the filter components. For example, for the first section

R_8 and $C_1 = C_2$ are chosen by the designer

$K_1 = K_2$ are chosen by the designer

Then:

$$R_1 = \frac{1}{b_1} C$$

$$R_2 = \frac{K_1}{\sqrt{b_0}\, C_2}$$

$$R_3 = \frac{1}{K_1 K_2 \sqrt{b_0}\, C_1}$$

$$R_4 = \frac{1}{K_2 C_1}$$

$$R_5 = R_6 = \infty \text{ [i.e. open circuit]}$$

$$R_7 = K_2 R_8$$

The foregoing is one non-limiting example of how one can design a bandpass filter which is useful in accordance with the principles of the invention, and various alternate design techniques can be employed.

Referring now to Fig. 8, there is shown an embodiment of the variable loopwidth carrier tracking loop 120 (Fig. 3) in accordance with the invention. A squaring circuit 201 receives the output of the AGC amplifier 115 (Fig. 3); i.e., the filtered, gain controlled PSK modulated signal. The squaring operation serves to substantially remove the modulation from the carrier and, in the process, also doubles the frequency of the carrier. The output of squaring circuit 201 is one input to a phase detector 202. The other input to phase detector 202 is the output of a frequency divider (or clock divider) 203. The output of phase detector 202 is coupled to a novel variable loopwidth filter 300, which will be described in detail below. The output of filter 300 is coupled to voltage controlled oscillator (VCO) 204, and the output of the VCO 204 is, in turn, coupled to the clock divider 203.

The loopwidth of variable loopwidth filter 300 can be adjusted either manually or automatically under control of loopwidth control unit 205. In the automatic mode of operation, the loopwidth control unit 205 receives the output of signal loss detector 206. The signal loss detector 206 includes a comparator which detects loss of lock in the loop by comparing the input signal (from AGC amplifier 115) with an adjustable threshold level. When the input signal is less than the threshold level, a loss of lock is indicated. The loopwidth control unit 205 is responsive to a signal loss indication to effect a loopwidth modification of variable loopwidth filter 300 to a wider loopwidth. When lock has been reacquired, or, for example, after a predetermined time when there will be a high probability that lock has been reacquired, the loopwidth control unit 205 effects a loopwidth modification of variable loopwidth filter 300 to a narrower loopwidth. In the manual mode of operation, switching is under manual control by a switch 205A.

The loopwidth (or bandwidth) of the phase locked loop generally determines the acquisition (or ''lock-up'') time of the loop, and also determines the stability of the loop; i.e., its ability to maintain lock in the presence of a noisy input. As noted above, a wider loopwidth is advantageous in acquiring lock quickly, but once lock is acquired the wider loopwidth is disadvantageous in that it results in lower stability than a phase locked loop having a narrower loopwidth. It is therefore advantageous to utilize wide loopwidth when acquiring lock, and then switch to a narrower loopwidth after lock is acquired so as to enhance the stability of the loop. In the present invention, modifications of the loopwidth can be performed automatically. An important feature of the invention prevents the switching between different loopwidths from introducing offset voltages in the loop which could cause a loss of lock.

To better understand the invention, it is useful to initially consider the basic loopwidth filter illustrated in Fig. 9. The output of phase detector 202 (Fig. 8) is an input to the positive input terminal of an operational amplifier 401. The negative input terminal of the operational amplifier 401 is fed back from the output of the amplifier via a capacitor C. The output of operational amplifier 401 is also coupled, via a gain control resistor network 402 (shown in dashed line), to the positive input terminal of another operational amplifier 405. The gain control network, in this simplified illustration, includes a series resistor designated R_2 and a resistor, designated R_1, which is coupled to ground reference potential. The output of operational amplifier 405 is fed back to the negative input terminal thereof. The output of operational amplifier 405 is also coupled via a voltage divider, consisting of series resistors labelled 99R and R, to

ground reference potential. The junction between the resistors of the voltage divider is coupled back to the negative input terminal of the operational amplifier 401. The transfer function of the loopwidth filter of Fig. 9 is

$$F(S) = \frac{A(S + 1/RC)}{(S + A/100RC)}$$

When integrated into the phase locked loop of Fig. 8, the closed-loop transfer function may be expressed as

$$H(S) = \frac{AK(S + 1/RC)}{(S^2 + AKS + AK/RC)}$$

where A is a gain factor that is less than or equal to unity, as controlled by the unit 402, and K is a loop gain constant which varies in proportion to the VCO frequency. It can be readily demonstrated that the loopwidth may be changed, without affecting the damping factor of the loop, if A and either R or C are varied in inverse proportion to each other. Typically, A and C can be varied in discrete steps. However, as noted in the Background portion hereof, switching of the loopwidth during operation can result in loss of data due to loss of lock caused by an offset voltage in the loopwidth filter when the loopwidth is switched. For example, in Fig. 9 assume a particular voltage exists across the capacitor C in the loop filter. To change loopwidth, another capacitor will typically be switched into the loop filter circuit (in place of C) and, simultaneously, the gain factor of loop filter will be changed. When this is done, a different voltage will be applied across the "new" capacitor. If the initial voltage applied across the new capacitor is not an appropriate value, the change in gain factor can result in a spurious error signal in the loop which causes lock to be lost.

Referring to Fig. 10, there is shown an embodiment of an adaptive loopwidth filter which includes a feature of the invention whereby capacitors are precharged to prevent loss of lock when switching to a different loopwidth. The operational amplifiers 401 and 405, and the resistors designated as 99R and R are he same as in Fig. 9. The resistor R_1 of the gain control network A of Fig. 9 is replaced by three individual resistors coupled to ground through a three position pole portion 480A of a switch 480. Depending on the switch position, one of three resistors designated R_{11}, R_{12}, and R_{13} are coupled between the positive input terminal of amplifier 405 and ground reference potential. The capacitors C_{11}, C_{12}, and C_{13} can be visualized as replacing the capacitor C of Fig. 6. By operation of the switch portions 480B, 480C and 480D of switch 480, one of these capacitors is seen to be coupled between the negative input terminal of operational amplifier 401 and a point which is a fixed voltage above the output of the operational amplifier 401. This fixed voltage may be, for example, 5.1 volts, by operation of the zener diode 412 and current sources 415 and 416. The positions of the various portions of switch 480 in the embodiment of Fig. 10 are under common control. The three positions of the switch are designated as "w" (wide), "m" (medium), and "n" (narrow) which represent the available loopwidth settings of the circuit for this embodiment. The control of the switch can be either manual or automatic, as effected by the loopwidth control circuit 205 (Fig. 8). It can be seen that when switch control is in the "w" (wide) position, resistor R_{11} and capacitor C_{11} are in the loop, when the switch control is in the "m" (medium) position the resistor R_{12} and capacitor C_{12} are in the loop, and when the switch control is at the "n" (narrow) position, the resistor R_{13} and capacitor C_{13} are in the loop. At relatively low frequencies of operation, such as are employed in a logging-while-drilling operation of the type described herein, relatively high values of capacitance are employed. For example, C_{11}, C_{12} and C_{13} may respectively have values of 10, 33 and 100 microfarads. To avoid exceedingly large physical capacitor sizes, it is practical to employ electrolytic type capacitors, these capacitors requiring a bias voltage, as is provided in the circuit of Fig. 10 by bias current sources 415 and 416 and zener diode 412. A filter capacitor 413, which typically has a large value such as 220 microfarads, is coupled in parallel with zener diode 412. The individual resistors, R_{11}, R_{12} and R_{13}, may have the values of infinite resistance (open circuit), 3.86K ohms and 1.00K ohms, respectively, and the resistor 414 may have a value of 9.09K.

Based on the portion of the Fig. 10 circuitry described thus far, assume that the adaptive loopwidth filter is operating in its "wide" loopwidth, that is with resistor R_{11} (open circuit) and capacitor C_{11} in the circuit. If the output of operational amplifier 401 is at a voltage V_1, and since the input impedance to operational amplifier 405 is very high, the voltage at the input of operational amplifier 405 is also approximately V_1. Assume now that loopwidth switch control of switch 480 is switched to the "medium" loopwidth position. The resistor R_{12} will now form a voltage divider with the resistor 414. Since R_{12} is only three-tenths of the total resistance of resistor 414 plus R_{12}, the voltage at the input to operational amplifier 405 would drop to a value of about (0.3) V_1. The output of operational amplifier 405 would therefore be instantaneously reduced to three-tenths of its previous value. This jumps, by itself, could cause loss of lock since the output of amplifier

405 is coupled to the loop VCO (Fig. 5). The positive side of the capacitor C_{12}, which will be switched into the circuit, is 5.1 volts above voltage V_1 (as is the positive side of capacitor C_{11} which is being switched out of the circuit). To avoid a sudden jump at the output of amplifier 405, the initial voltage across C_{12} should be greater than the voltage was across C_{11} by a factor of 10/3. Accordingly, and as will be described momentarily, the present invention provides appropriate precharging of the capacitors which are not currently operative in the circuit. However, a further consideration should be taken into account as follows: Two signal components are generally present in the loop filter circuit, namely an AC signal component and a DC or very low frequency error voltage. Since the positive-going side of all three capacitors, C_{11}, C_{12}, and C_{13}, are coupled to a common point (i.e. 5.1 volts above the output voltage of operational amplifier 401), care must be taken not to precharge the inoperative capacitors (i.e., those which are temporarily out of the circuit) to a fixed gain times both components, since the AC component is a common mode signal which should remain the same regardless of the selected loopwidth.

In the circuit of Fig. 10, a voltage representative of the voltage across the capacitor currently in the circuit is applied to each of a plurality of gain control amplifiers 421, 423 and 425. In particular, the voltage which is 5.1 volts below the voltage on the positive side of the capacitor currently in the circuit is applied to the positive input terminal of each of these amplifiers 421, 423 and 425, and the voltage at the negative input terminal of operational amplifier 401 (which is also the voltage at the negative side of the capacitor currently in the circuit) is applied to the negative input terminal of each of the amplifiers 421, 423 and 425. Three further portions of switch 480, designated 480E, 480F and 480G, are operative to apply one of three gain control inputs to a gain control terminal of each of the respective amplifiers 421, 423 and 425. In the present embodiment, the gain control multipliers applied to amplifier 421 for the switch positions "w", "m" and "n" are 1.0, 0.3 and 0.1, respectively. The gain control multipliers applied to the amplifier 423 for the switch positions "w", "m" and "n", are 3.3, 1.0 and 0.33, respectively. The gain control multipliers applied to the amplifier 425 for the switch positions "w", "m" and "n" are 10, 3.0 and 1.0, respectively. It will be understood that the gain control multipliers applied to the gain control amplifiers 421, 423 and 425, via the switch portions 480E, 480F and 480G, respectively, can be generated by any suitable means known in the art, such as by switching appropriate weighting resistors (not shown) into voltage divider circuits to obtain the desired gain multipliers.

The outputs of amplifiers 421, 423 and 425 are respectively coupled to the negative input terminals of operational amplifiers 422, 424 and 426. The positive input terminals of these amplifiers are each coupled to the output of operational amplifier 401, so they each receive a signal which is 5.1 volts below the voltage on the positive side of the capacitor currently in the circuit. The outputs of amplifiers 422, 424 and 426 are respectively coupled to two poles of the respective switch portions 480B, 480C and 480D. The three switch portions are seen to be arranged such that the negative terminals of the capacitors which are not currently operative in the loop filter circuit are coupled to the output of their respective amplifiers (422, 424 or 426). Specifically, capacitor C_{11} is coupled to the output of amplifier 422 for the "m" and "n" switch positions, capacitor C_{12} is coupled to the output of amplifier 424 for the "w" and "n" switch positions, and the capacitor C_{13} is coupled to the output of the amplifier 426 for the "w" and "m" switch positions.

In operation, the switch 480 is seen to cause switching of the filter loopwidth by simultaneously switching in the appropriate gain factor (resistor R_{11}, R_{12} or R_{13}) along with its corresponding capacitor (C_{11}, C_{12} or C_{13}). The switch portions 480B, 480C and 480D also serve to apply the desired precharging voltages to those capacitors not currently in the circuit. This is achieved by the amplifiers 421 through 426. In particular, the positive terminals of these six amplifiers are coupled to a potential which is 5.1 volts below the voltage on the positive plates of each of the three capacitors C_{11}, C_{12} and C_{13}. The negative input terminal of the amplifiers 422, 424 and 426 are coupled to the potential on the negative plate of the particular capacitor (C_{11}, C_{12} or C_{13}) which is currently in the circuit. Since the outputs of amplifiers 421, 423 and 425 are respectively coupled to the negative input terminals of amplifiers 422, 424 and 426, it is seen that the common mode AC signal component is cancelled in the output of amplifiers 422, 424 and 426, and not applied as a precharging voltage.

An example of operation is as follows: Assume once again that the circuit is operating in the "wide" loopwidth, that is with R_{11} (open circuit) and capacitor C_{11} in the circuit. As described above, a switch to the "medium" loopwidth would require an initial voltage across C_{12} (the "new" capacitor in the circuit) which is 10/3 (= 3.3) times the value which had been applied across C_{11} just before switching. It is seen that in this situation a gain control factor of 3.3 is applied to amplifier 423 via switch portion 480F. If switching were, instead, to the "narrow" loopwidth, the resistor R_{13} switched into the circuit would, by itself, cause the input voltage to amplifier 505

to drop to 1/10 of its value just before switching. Accordingly, the gain control factor applied to amplifier 425 (affecting the pre-charging of capacitor C_{13} which would be switched in in this situation) has a value of 10. The remaining gain control factors for the amplifiers 421, 422 and 423 can also be readily seen to have the appropriate values for each situation.

A further feature of the improved carrier tracking loop (e.g. blcok 120 of Fig. 3) in accordance with another aspect of the present invention will now be discussed. Fig. 11 illustrates a conventional prior art carrier tracking loop circuit. It will be apparent that it corresponds to the circuit illustrated in Fig. 8 but without signal loss detector 206, loopwidth control 205A, and variable loopwidth filter 300. Accordingly, the same numbers have been used for similar components. The modulated carrier is first squared by a squaring circuit 201 to destroy the modulation information contained therein. The output of squaring circuit 201 is a signal at about twice the carrier frequency, and is one input to a phase comparator 202. The output of the phase comparator is coupled to a loop filter 203 whose output is, in turn, coupled to the control input terminal of a voltage controlled oscillator (VCO) 204. The output of the VCO is coupled, via a frequency divider (or clock divider) 205, to the other input of phase comparator 202. In operation, and as is well known, once lock is achieved the phase locked loop of Fig. 11 stays locked onto the carrier since phase differences between the generated clock signals (output from clock divider 205) and the received carrier produce an error signal which tends to adjust the VCO frequency to correct any sensed "error". However, as noted in the Background portion hereof, the unidirectional nature of the phase modulation in the type of system described herein tends to cause a problem in operation of the phase locked loop. In particular, since changes are implemented (at data transitions) by momentary variation of frequency (to a lower frequency in the present embodiment), error pulses are generated at the output of the phase comparator each time a data transition occurs. Since the PSK modulation is unidirectional (i.e., momentary frequency modification is always to a lower frequency—as herein—or always to a higher frequency) these error pulses always have the same polarity. Applicants have noted that these error pulses can tend to pull the carrier tracking loop off in frequency.

Fig. 12 shows an improved carrier tracking loop circuit wherein means responsive to transitions in the received signal are provided for compensating the signal applied to the control terminal of the VCO to account for the difference between the nominal frequency of the carrier and the actual average frequency of the received signal. In Fig. 12, the squaring circuit, phase comparator, loop filter, voltage controlled oscillator, and clock divider all have the same reference numerals as in Fig. 11.

In the embodiment of Fig. 12, the output of phase comparator 202 is applied to the loop filter and VCO via a summing circuit 210. The other input to summing circuit 210 receives compensating pulses from a pulse generator 220. The pulse generator 220, which may be a monostable or "one shot" multivibrator, is triggered by the output of bit transition detector 150 (Fig. 3) via line 222 and produces a short compensating pulse each time a data transition occurs. In this manner, the effect of the previously described error pulses does not accumulate and cause a frequency drift of the phase locked loop. Fig. 13 shows the waveform which is output from summing circuit 210. The error pulses 1, 2 and 3, which occur at data transitions, are compensated for by the pulses 1', 2' and 3' which are produced by pulse generator 220. The net input to the VCO, resulting from the frequency-modifying nature of the phase modulation, is therefore substantially zero.

CLAIMS

1. A method utilizing a PSK signal that has been modulated with digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carier signal as a function of the digital information to effect a phase change; characterized by the steps of:

filtering the modulated carrier signal with a filter having a bandpass center frequency which is offset from the nominal carrier frequency in the direction of said unidirectional decrease or increase of frequency; and

recovering the digital information from the filtered signal.

2. A method of claim 1, characterized by offsetting the center frequency from the nominal carrier frequency by an amount which is a function of the bit rate of said digital information.

3. The method of claim 2, characterized in that the offset amount is equal to one-half the bit rate of said digital information.

4. The method of claim 1, 2 or 3, characterized by skewing the bandpass characteristics of said filter in the same direction as said offset.

5. A method utilizing a PSK signal that has been modulated with digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; characterized by the steps of:

filtering the modulated carrier signal with a filter having a bandpass characteristic which is skewed in the direction of said unidirectional

decrease or increase of frequency; and
recovering the digital information from the filtered signal.

6. A method for reducing transient signals that result from switching a different capacitor into a circuit for use in an electronic system which includes: a pair of terminals; a plurality of capacitors, each of said capacitors having one of its plates coupled to one of said terminals; switching means for coupling the other plate of a selected one of said capacitors to the other terminal; and variable gain means synchronized with said switching means and affecting the potential of said other terminal; said method being characterized by the steps:

continuously generating a reference voltage associated with each of said plurality of capacitors not presently coupled between said pair of terminals, each said generated reference voltage being a function of the voltage which would appear across its associated capacitor in the event said associated capacitor were instantaneously switched by said switching means between said pair of terminals; and

continuously applying each said generated reference voltage across its associated capacitor.

7. A method of stabilizing a carrier tracking loop used in conjunction with an apparatus which receives a PSK signal that was modulated with digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; said apparatus including a carrier tracking loop circuit for tracking the carrier of the received signal, said carrier tracking loop circuit including a controlled oscillator having a control terminal, the frequency of said oscillator being determined by a signal applied to said control terminal, a comparator for generating a control signal by comparing the phase of a signal derived from the received PSK modulated signal to the phase of a signal derived from the output of said controlled oscillator, and means for applying said control signal to the control terminal of said oscillator; said method being characterized by the steps of:

generating compensating pulses in response to transitions in the received signal; and

applying said compensating pulses to said control terminal to account for the difference between the nominal frequency of said carrier and the average frequency of the received signal which result from the unidirectional nature of the carrier modulation.

8. An apparatus which receives a PSK signal modulated with digital information and is operative to recover the digital information therefrom, said PSK modulated signal having been modulated with the digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; said apparatus including a filter for use in selectively filtering the modulated carrier signal; characterized by said filter having a bandpass center frequency which is offset from the nominal carrier frequency in the direction of said unidirectional decrease or increase of frequency.

9. The apparatus as defined by claim 8 characterized in that said center frequency is offset from the nominal carrier frequency by an amount which is a function of the bit rate of said digital information.

10. The apparatus as defined by claim 9 characterized in that said center frequency is offset from the nominal carrier frequency by an amount equal to one-half the bit rate of said digital information.

11. The apparatus as defined by claims 8, 9 or 10 characterized in that the bandpass characteristic of said filter is skewed in the same direction as said offset.

12. The apparatus as defined by claim 8, wherein said apparatus includes a logging-while-drilling apparatus for obtaining subsurface measurements during drilling in a fluid-filled borehole and for communicating the measurements to the surface of the earth, comprising:

a downhole sensing and transmitting subsystem including

means mountable on a drill string for obtaining measurement information;

means for generating acoustic carrier waves at a nominal frequency in the borehole fluid;

means for PSK modulating the generated acoustic carrier waves in accordance with digital data representative of said measurements by momentarily unidirectionally either decreasing or increasing the frequency of said acoustic carrier signal; and an uphole receiving subsystem including said filter and

transducer means for converting the modulated acoustic carrier waves to electronic signals; and

characterized in that the center frequency of said filter is offset from the nominal carrier frequency by an amount which is a function of the bit rate of said digital information; and

means for extracting the digital data from the filtered electronic signals.

13. An apparatus for demodulating a digital signal which receives a PSK signal modulated with digital information and is operative to recover the digital information therefrom, said PSK modulated signal having been modulated with the digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; and then returning the carrier to nominal frequency once the phase change has been effected; said apparatus including a filter for use in selectively filtering the modulated carrier signal; charac-

terized by said filter having a bandpass characteristic which is skewed in the direction of said unidirection decrease or increase of frequency.

14. An electronic system which includes: a pair of terminals; a plurality of capacitors, each of said capacitors having one of its plates coupled to one of said terminals; switching means for coupling the other plate of a selected one of said capacitors to the other terminal; and variable gain means synchronized with said switching means and affecting the potential of said other terminal; said system being characterized by a circuit for reducing transient signals that result from switching a different capacitor between said pair of terminals, comprising:

means for continuously generating a reference voltage associated with each of said plurality of capacitors not presently coupled between said pair of terminals, each said generated reference voltage being a function of the voltage which would appear across its associated capacitor in the event said associated capacitor were instantaneously switched by said switching means between said pair of terminals; and

means for continuously applying each said generated reference voltage across its associated capacitor.

15. The system as defined by claim 14 characterized in that said means for generating a reference voltage is responsive to the voltage currently across said pair of terminals and is also responsive to a ratio of the gain factors of said variable gain means.

16. The system as defined by claim 15 characterized in that said means for generating a reference voltage comprises a plurality of amplifier means, each of said amplifier means being responsive to the present voltage between said pair of terminals and being gain controlled in accordance with a ratio of said gain factors.

17. The system as defined by claims 14, 15 or 16 characterized in that the positive plate of each of said capacitors is coupled to said one of said pair of terminals and said one terminal is maintained at a positive voltage.

18. A variable loopwidth carrier tracking loop for locking onto the carrier of an input signal, comprising:

a phase-locked loop including an oscillator having a control input, error signal generating means for generating an error signal as a function of the phase difference between a signal as a function of the phase difference between a signal derived from said oscillator and the input signal, and a variable filter having a plurality of different bandwidths for coupling the output of said error signal generating means to the control input of said oscillator; and characterized by:

loopwidth control means coupled to said variable filter for automatically changing the loopwidth of said filter as a function of the input signal.

19. The tracking loop as defined by claim 18 characterized in that said variable filter includes a plurality of capacitors which are switchably coupled into and out of operation in said filter under control of said loopwidth control means, and wherein said variable filter includes means for continuously precharging those of said capacitors which are not presently operational in the filter so as to prevent loss of lock in said phase-locked loop when switching is effected by said loopwidth control means.

20. The tracking loop as defined by claim 18 wherein said variable filter comprises:

a first amplifier having first and second input terminals, said first input terminal being adapted to receive an input signal;

a second amplifier;

variable gain control means for switchably coupling the output of said first amplifier to an input of said second amplifier, said variable gain control means having at least first and second different gain factors;

variable capacitance means including at least first and second capacitors, one of which is switchable in concert with said variable gain control means to capacitively couple the output of said first amplifier to the second input terminal of said first amplifier; and characterized by:

means for generating a reference voltage associated with the capacitor which is not presently operative in said variable capacitance means, said generated referenced voltage being a function of the voltage which would appear across the capacitor not currently operative in the event it were instantaneously switched into operation; and

means for continuously applying the generated reference voltage across the capacitor not currently operative in said variable capacitance means.

21. The tracking loop as defined by claim 20 characterized in that said means for generating a reference voltage is responsive to the voltage across the capacitor currently operative in said variable capacitance means and is also responsive to a ratio of said gain factors.

22. The tracking loop as defined by claim 20 characterized in that said means for generating a reference voltage comprises first and second amplifier means respectively associated with said first and second capacitors, the amplifier means associated with the capacitor not currently operative being responsive to the voltage across the currently operative capacitor.

23. The tracking loop as defined by claim 22 characterized in that wherein each of said amplifier means is gain controlled in accordance with a different ratio of said gain factors.

24. An apparatus which received a PSK

signal modulated with digital information and is operative to recover the digital information therefrom, said PSK modulated signal having been modulated with the digital information by momentarily unidirectionally either decreasing or increasing the nominal frequency of a carrier signal as a function of the digital information to effect a phase change; said apparatus including a carrier tracking loop circuit, comprising:

a controlled oscillator having a control terminal, the frequency of said oscillator being determined by a signal applied to said control terminal;

comparator means for generating a control signal by comparing the phase of a signal derived from the received PSK modulated signal to the phase of a signal derived from the output of said controlled oscillator;

means for applying said control signal to the control terminal of said oscillator; and characterized by

means responsive to transitions in the received signal for compensating the signal applied to said control terminal to account for the difference between the nominal frequency of said carrier and the average frequency of the received signal which result from the unidirectional nature of the carrier modulation.

25. The circuit as defined by claim 24 characterized in that said compensating means comprises means for generating a pulse at each data transition of the received signal, and means for adding the generated pulses to said control signal.

26. The apparatus of claim 24 including a logging-while-drilling apparatus for obtaining subsurface measurements during drilling in a fluid-filled borehole and for communicating the measurements to the surface of the earth, comprising:

a downhole sensing and transmitting subsystem including means mountable on a drill string for obtaining measurement information;

means for generating acoustic carrier waves at a nominal frequency in the borehole fluid;

means for PSK modulating the generated acoustic carrier waves in accordance with digital data representative of said measurements by momentarily unidirectionally either decreasing or increasing the frequency of said acoustic carrier signal; and an uphole receiving subsystem including

transducer means for converting the modulated acoustic carrier waves to an input electronic signal; and

a carrier tracking loop circuit which includes said controlled oscillator said comparator means, said applying means, and said compensating means, and characterized in that said compensating means comprises means for generating a pulse at each data transition of the received signal, and means for adding the generated pulses to said control signals; and

means for recovering the digital data by demodulating said input signal with a signal derived from the output of said controlled oscillator.

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